GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 10, 10.1029/2001GL014056, 2002

Is desert dust making oligotrophic waters greener?

H. Claustre,[1] A. Morel,[1] S. B. Hooker,[2] M. Babin,[1] D. Antoine,[1] K. Oubelkheir,[1]
A. Bricaud,[1] K. Leblanc,[3] B. Quéguiner,[3] and S. Maritorena[4]

Received 8 September 2001; accepted 28 January 2002; published 28 May 2002.

[1] In situ optical measurements provide evidence that oligotrophic waters of the Mediterranean Sea have a greener color than would result from their phytoplankton content alone. This anomaly, detectable in low chlorophyll waters, remains unnoticed in the chlorophyll-rich waters of the nearby waters of the Moroccan upwelling zone. It is due to enhanced absorption in the blue and enhanced backscattering in the green parts of the visible spectrum likely resulting from the presence of submicron Saharan dust in suspension within the upper layer. This result implies that regional estimations of carbon fixation from ocean color images might be significantly overestimated, not only in the Mediterranean Sea, but also in other oligotrophic areas of the Northern hemisphere, subjected to desert dust deposition. *INDEX TERMS:* 4552 Oceanography: Physical: Ocean optics; 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 1640 Global Change: Remote sensing

1. Introduction

[2] Brick-red or pink dust massively exported from the Sahara is at the origin of the so-called "red-rains", sporadically falling over Europe. Besides this spectacular effect, Saharan dust influences several atmospheric and marine processes, such as regional radiative budgets [*Legrand et al.*, 1992], the formation of clouds and rain [*Levin and Ganor*, 1996], the acidity of rainfall [*Loÿe-Pilot et al.*, 1986]. Dust deposition also affects sedimentary processes and the biogeochemistry of the Mediterranean Sea, including, perhaps, its productivity through iron enrichment of surface waters [*Guerzoni et al.*, 1997]. Desert dust also impacts optical properties of the atmosphere, leading to some biases in the retrieval of the chlorophyll *a* concentration ($\langle$Chl*a*$\rangle$) from color images of the upper ocean [*Moulin et al.*, 2001].

[3] The possible effect of desert dust on optical properties of oceanic waters remains however unknown. Therefore, one of the objectives of the PROSOPE (French acronym for Productivity of Pelagic Oceanic Systems) cruise (Figure 1) was to examine if any peculiar optical characteristic caused by Saharan dust deposition could be detected in oligotrophic Mediterranean waters, that would bias the optical assessment (in situ or remotely) of $\langle$Chl*a*$\rangle$.

2. Methods-Background

[4] The cruise took place from 4 September to 4 October, 1999. The upwelling waters off Morocco (UPW station) were sampled over 3 days, and the MIO (Ionian Sea, eastern basin) and DYF (Ligurian Sea, western basin) stations were occupied for 5 days each. Short intermediate stations (St 1 to St 9) were sampled over 4-h periods. Optical measurements and pigment sampling were always performed around noon, within 1 h of overflight by the SeaWiFS satellite.

[5] $\langle$Chl*a*$\rangle$ was analysed according to a slightly modified version of the HPLC method described by *Vidussi et al.* [1996]. The accuracy of $\langle$Chl*a*$\rangle$ measurements (8%) was checked as part of an international intercomparison exercise (four laboratories were involved) performed on samples taken during the cruise [*Hooker et al.*, 2001].

[6] In situ spectral measurements of upwelling irradiance or radiance and downwelling irradiance were performed using three instruments: LI-1800 LICOR, Satlantic LoCNESS and Satlantic SeaFALLS.

[7] The reflectance of a water body, R(λ), is defined as the ratio of upwelling irradiance (or radiance) to downwelling irradiance, and the spectral shape of R(λ) define the so-called "water color". This color is indexed by the blue-to-green reflectance ratio (B/G), R(443)/R(555), which, in open-ocean (Case-1) water is essentially governed by the phytoplankton content (actually B/G decreases with increasing phytoplankton content). Therefore, algorithms have been developed that relate surface $\langle$Chl*a*$\rangle$ to B/G [*O'Reilly et al.*, 1998; *Morel and Maritorena*, 2001]. R(λ) is approximately proportional to the ratio of the backscattering and absorption coefficients, $b_b(\lambda)/a(\lambda)$.

3. Results

[8] The PROSOPE data set spans two orders of magnitude in surface $\langle$Chl*a*$\rangle$ (0.03 to 3.75 mg m^{-3}) and about one order of magnitude in B/G (0.5 to 6.7) (Figure 2). Data collected in the upwelling (station UPW) off Morocco, are in close agreement with global algorithms (Figure 2). This is no longer the case for Mediterranean waters which look systematically greener (lower B/G) than typical oceanic waters with the same $\langle$Chl*a*$\rangle$, as already observed by *Gitelson et al.* [1996] for the eastern Mediterranean sea. As a consequence, derivation of $\langle$Chl*a*$\rangle$ from B/G measurements through conventional algorithms overestimates actual $\langle$Chl*a*$\rangle$ in Mediterranean waters by a factor exceeding 2 (Table 1).

[9] For a given $\langle$Chl*a*$\rangle$, a lower than expected B/G (Figure 2) is due to a lower than expected $b_b(440)/b_b(555)$ and/or a lower than expected a(555)/a(440). When compared to optical properties modeled for a standard ocean with similar $\langle$Chl*a*$\rangle$, PROSOPE data show two important features (Table 1): (i) the color shift is caused by both anomalous absorption and backscattering ratios (Mediterranean waters absorb more blue light and backscatter more green light than anticipated); and (ii) the particle scattering coefficients, $b_p(555)$, are anomalously high compared to those modeled for a standard ocean.

[10] Additional absorption measurements performed during the cruise permitted an inquiry into the substance(s) potentially responsible for the B/G changes. An absorption budget can be written as:

$$a(\lambda) = a_W(\lambda) + a_P(\lambda) + a_{OS}(\lambda) \tag{1}$$

[1]Laboratoire d'Océanographie de Villefranche, Villefranche-sur-mer, France.
[2]Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, MD, USA.
[3]Laboratoire d'Océanographie et de Biogéochimie, Marseille, France.
[4]Institute for Computational Earth System Science, University of California, Santa Barbara, CA, USA.

0094-8276/02/2001GL014056$05.00

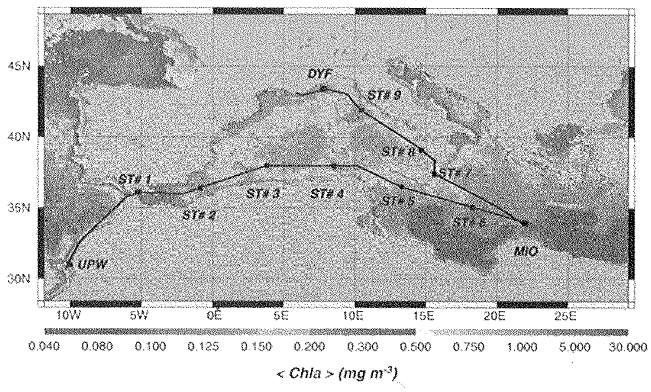

Figure 1. PROSOPE cruise track superimposed on the composite SeaWiFS image of surface ⟨Chl*a*⟩ for September 1999. This composite was derived from SeaWiFS reflectances using the OC4v4 algorithm [*O'Reilly et al.*, 1998].

where $a(\lambda)$ is the total absorption, $a_W(\lambda)$ and $a_P(\lambda)$ are the absorption by water and particles (phytoplankton, heterotrophs, and associated biogenic detritus), respectively and $a_{OS}(\lambda)$ is a residual term accounting for "other substances". The latter can be estimated by subtraction, because $a_W(\lambda)$ is known and $a(\lambda)$ and $a_P(\lambda)$ were measured.

[11] The high $a_P(440)$ values (Table 1) result primarily from the presence of non-photosynthetic carotenoids, typical of algae in oligotrophic surface waters, and, to a lesser extent, from non-algal particles. Such a pigmentation slightly decreases the ratio a(555)/a(440). In open-ocean Case-1 waters, a_{OS} is generally believed to result from the presence of colored dissolved organic matter (CDOM). However, the PROSOPE $a_{OS}(440)$ values are inappropriately high when compared to modeled $a_{CDOM}(440)$ values for standard oceanic waters. Moreover, high CDOM content is unlikely for two reasons: (i) CDOM is a by-product of biological activity, which is rather low in the Mediterranean; and (ii) CDOM is exposed to intense photo-bleaching [*Vodacek et al.*, 1997], favored by the summer vertical stratification combined with high surface irradiance. In addition, CDOM has no scattering capability able to account for the high $b_p(555)$ value as well as for the unexpectedly low $b_b(440)/b_b(555)$ ratio, also observed. The presence of bubbles could be put forward to account for the enhanced scattering coefficient [*Zhang et al.*, 1998]. It is unlikely, however, as the conditions during the cruise were exceptionally good in term of sea state and ambient wind.

[12] Given that algal, non-algal particles, CDOM and bubbles are not plausible causes for concomitant decreases in both a(555)/a(440) and $b_b(440)/b_b(555)$, and for enhanced $b_p(555)$ values, "other substances" have to be found to explain the conspicuous green color shift. We suggest that submicron Saharan dust, probably smaller than 0.7 μm [*D'Almeda, and Schütz*, 1983; *Gomes et al.*, 1990], is responsible for this unexpected observation.

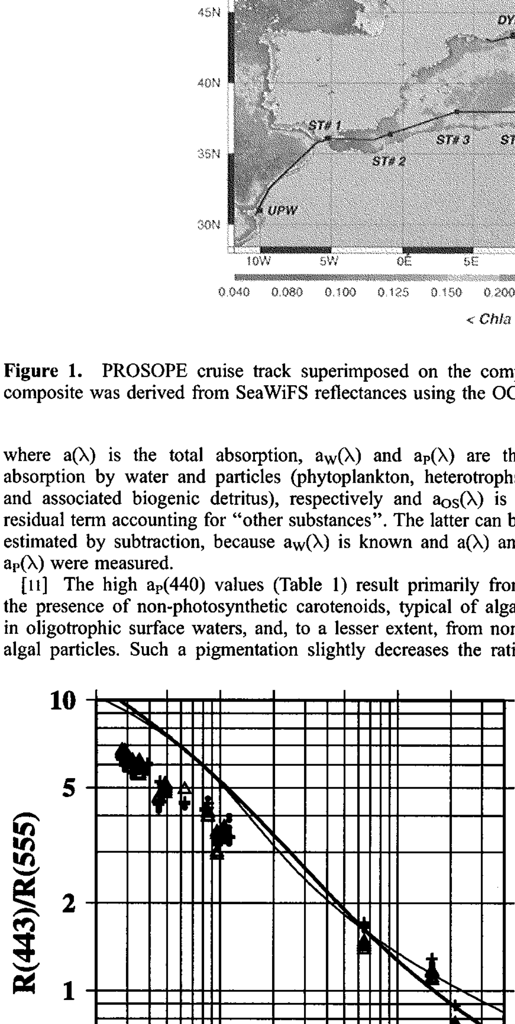

Figure 2. Relationship between surface ⟨Chl*a*⟩ and the blue-to-green reflectance ratio derived from in situ data (determined just below the surface). The ⟨Chl*a*⟩ values below 0.15 mg m^{-3} are from the Mediterranean, and values >0.6 mg m^{-3} are from the upwelling area off Morocco. The blue-to-green reflectance ratios were derived from spectral irradiance or radiance measurements performed by a LI-1800 LICOR (△), aSatlantic LoCNESS (▲) and aSatlantic SeaFALLS (+). The field data are compared to an empirical model [*O'Reilly et al.*, 1998] (algorithm OC4v4, thin line) and to a semi-analytical model [*Morel and Maritorena*, 2001] (thick line).

5. Concluding Remarks

[17] It has been shown that the presence of non-phytoplankton constituents — namely of dust — in open ocean waters with low ⟨Chl*a*⟩ can depress the in situ B/G compared to its expected value. Moreover, the remotely-sensed B/G can be even more lowered because the atmospheric correction of the blue bands is less accurate when absorbing aerosols are present in the atmosphere [*Moulin et al.*, 2001], which leads to an underevaluation of the actual B/G. This appears to be the case in oligotrophic Mediterranean waters where the ⟨Chl*a*⟩ retrieved from SeaWiFS (Figure 1) are distinctly higher than the sea truth data (Table 1). These observations suggest that regional algorithms are needed and that the dependence of ⟨Chl*a*⟩ retrieval on the proximity of desert dust sources must be systematically investigated. Given the large spatial extension of sub-tropical gyres, a proper estimation of their contribution to oceanic carbon fixation requires very accurate estimate of their surface ⟨Chl*a*⟩. A careful re-examination of their optical properties is, therefore, a prerequisite to address (and quantify) potential dust-induced bias in ⟨Chl*a*⟩ retrieval.